



Urbanization and seasonal effects on the lake ecosystem dynamics from 2002 to 2022 in Bengaluru, South India

Suman Kumar Sourav^a, Lily Clements^b, Thanh Thi Nguyen^{a,*}, Andreas Buerkert^a

^a Organic Plant Production and Agroecosystems, Research in the Tropics and Subtropics, Faculty of Organic Agricultural Sciences, University of Kassel, 37213 Witzenhausen, Germany

^b Innovations in Development, Education and the Mathematical Sciences - IDEMS International, RG2 7AX Reading, United Kingdom

ARTICLE INFO

Keywords:

Google earth images
Lake vegetation
Urban-rural- gradient
Urban wetland

ABSTRACT

Land use transformation in the rapidly growing megacity of Bengaluru in South India has greatly influenced its lake ecosystems. To gain insights into the dynamics of lake ecosystems along an urban-rural gradient, we analyzed lake-cover changes (along with a 300 m buffer zone) of six lakes from 2002 to 2022. The lakes studied were Bellandur and Dodda Bommasandra (urban), Attur and Puttenhalli (peri-urban), and Chudahalli and Vrishabhavathi (rural). Supervised maximum likelihood Land Use/Land Cover (LULC) classifications were conducted on 162 freely available, RGB Google Earth (GE) images to distinguish between macrophytes, algae, water, and dried land inside the lakes, and built-up and non built-up area in the buffer zone. Antagonistic relationships between macrophytes and algae were observed at all locations. Rainfall was positively correlated with the wet surface area (that is macrophytes, algae, and water) in comparatively dry lakes. Similarly, air temperature was negatively correlated with the wet surface area except for the Vrishabhavathi Lake. However, the built-up area in the buffer zone did not show a consistent correlation with the wet surface area, most likely because of sewage connections of certain lakes with distant urban areas.

1. Introduction

In 2023 of the currently eight billion on our planet approximately 4.6 billion, or 57 % are considered “urban” as they live in towns or cities. Latter figures are likely to surge by nearly 600 million, culminating in a total of 5.2 billion, or approximately 60 %. Following this trend, India’s urban population is expected to reach 607 million by 2030, with 40 % of the Indian population living in urban areas by mid-2030 (UN, 2019).

As urban areas continue to grow, water bodies undergo severe transformation due to the discharge of urban wastewater and pollutants (He et al., 2011; Naselli-Flores, 2008; Martínez-Arroyo and Jáuregui, 2000). In Bengaluru referred to as India’s “Silicon Valley” the “City of Lakes” urbanization has significantly altered the structure of the urban and peri-urban landscapes (Sen and Nagendra, 2021; Ramachandra and Aithal, 2019). The pace of urbanization was driven by economic liberalization in the early 1990s, coinciding with the advent and rapid growth of the information technology (IT) and related industries (Sudhira et al., 2003). Bharadwaj et al. (2022) identified that 37.8 % of Bengaluru’s growth occurred as edge expansion, a peculiar pattern of outward growth of cities in many countries of the Global South

(Chakraborty, 2022). Hereby, Bengaluru is one of Asia’s fastest-growing megacities with currently around 13 million inhabitants, nearly doubling populace from 2002 (UN, 2022). It lies 920 m above sea level in the southern part of the Deccan Plateau, which is formed of sheets of massive granite rocks lying under a thin surface layer of soil.

The lakes in Bengaluru are primarily man-made, interconnected through storm water drains which carry excess water from higher to lower elevations. Over time, these lakes have provided various ecological services and supported local livelihoods (Nagendra et al., 2013; McDonald et al., 2011). In the past, agrarian communities clustered around the lakes, relying on them as a source of irrigation water, fertilizer from silts scraped from the lakebed, grass or fodder, drinking and cleaning water, and fishing. Present-day, the lakes are mostly used by urban communities for recreational purposes such as walking, boating, yoga, bird watching, and cultural events (Sen and Nagendra, 2021). Beyond the direct benefits provided by the lakes, there are some indirect benefits to the surrounding environment such as flood control (Dittrich, 2007), groundwater recharge (Sudhira and Nagendra, 2013), wastewater treatment (Ramachandra et al., 2016a), lower ambient temperature (Parikh et al., 2015), and biodiversity conservation (Hettiarachchi,

* Corresponding author.

E-mail address: tropcrops@uni-kassel.de (T.T. Nguyen).

<https://doi.org/10.1016/j.envc.2024.100944>

Received 12 February 2024; Received in revised form 23 March 2024; Accepted 17 May 2024

Available online 18 May 2024

2667-0100/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

2014).

Over the last decades the water demand by Bengaluru's population has increased exorbitantly, yet the integration of the water bodies into the supply and reuse remains inadequate (Unnikrishnan et al., 2017). As a result, private borewells have been drilled up to a depth of 400 m, and additionally a 100 km long trench was built to extract the politically conflicted water resources of the Cauvery-Arkavathy river basins to meet the rising water demand of the city (Ramachandra et al., 2016b; Ramachandra and Aithal, 2016). The water commons of the city are becoming part of the public health concerns given contamination of surface and underground water (Goldman, 2011). Ramachandra et al. (2016a) reported that 98 % of lakes in Bengaluru are encroached, disrupting their interconnectivity. Furthermore, 90 % of the lakes have been polluted by untreated sewage, industrial effluents, and the dumping of solid wastes and building debris. Varalakshmi and Ganeshamurthy (2012) claimed that more than half of the city's lakes were highly polluted. Despite this pollution, local farmers use these lakes to collect fodders for their cattle, and extract contaminated irrigation water to irrigate their fields. This can lead to the accumulation of toxins in the soil, lower the yield of crops, generate health issues, and cause marketing difficulties for local products (Varalakshmi and Ganeshamurthy, 2012).

In wetlands aquatic macrophytes have several ecological functions (Carpenter and Lodge, 1986). They aid in the sequestration of organic carbon and nutrients, stabilization of sediments and shorelines (Søndergaard, 2010), and can be used as indicators of water quality (Brucet, 2013). In Bengaluru, a quarter of the lakes are fully covered by macrophytes, a phenomenon attributable to the rapid growth of exotic invasive species indicating lake degradation (Verma et al., 2003). Depending on the season the macrophyte cover in the wetlands of Bengaluru is dominated by a mixture of floating water hyacinth (*Eichhornia crassipes* (Mart.) Solms) and rooted alligator weed (*Alternanthera philoxeroides* (Mart.) Griseb.), nut grass (*Cyperus rotundus* L.), and narrow leaf cuttail (*Typha angustifolia* L.) along with *Chlorella* algae and a *Cyanophyceae* bacterial population (Mahapatra et al., 2018; Bhat et al., 2017; Ramachandra et al., 2017). The mixture of macrophytes and bacterial-algal communities of phytoplanktons play an important role in these lake ecosystems as they contribute to water purification (Mahapatra et al., 2018; Ramachandra et al., 2018, 2014, 2003). With the rapid spatial growth of macrophyte cover, the algal activity is lowered significantly which can lead to higher oxygen demand lake ecosystems (Mahapatra et al., 2018; Ramachandra et al., 2017).

Advances in remote sensing approaches and increasing availability of images with high spectral and temporal resolution have allowed to understand spatio-temporal variation in lake dimensions and cover as a consequence of urbanization (Bareuther et al., 2020; Gautam et al., 2015; Ramachandra and Kumar, 2008). The latter authors also reported that lake cover dynamics are more driven by seasonal monsoon-related factors than by differences in their waste water-related nutrient status.

In view of the above, this study aims to add a new dimension to the prevailing literature the effects of seasonality and urbanization within a 300 m buffer zone on lake ecosystem dynamics by using freely available Google Earth (GE) satellite images from 2002 to 2022. We hereby want to determine the effect of urbanization on wetland environments. Specifically, we aim to (i) determine seasonal and temporal dynamics of vegetation, and (ii) detect the proportion of built-up areas surrounding different lake types and siltation-derived dried-up lake shores along an urban-rural gradient of Bengaluru.

2. Materials and methods

2.1. Study locations

Bengaluru on the southern Indian Deccan Plateau has a mild climate throughout the year with temperatures ranging from 18 °C to 38 °C during the monsoonal summer and 12 °C to 25 °C during the dry winter

(Ramachandra and Aithal, 2019). Average annual precipitation is 900 mm, with the majority occurring between June and September (Ravindrababu et al., 2010). Along an urban-rural gradient defined according to Hoffmann et al. (2017) we selected six lakes with a buffer distance of 300 m from the lake boundary to determine typical urbanization effects on lake encroachment (Fig. 1).

2.2. Data collection

A total of 162 images of the six selected lakes from 2002 to 2022 were downloaded from GE Pro 7.1 whereby incomplete, blurred, and cloud-covered images were excluded (Table 1). The six lakes were divided into the three strata “urban”, “peri-urban”, and “rural” following Hoffmann et al. (2017). In each image, a set of ‘virtual’ Ground Truthing Points (GTPs) was determined to allow for training and accuracy assessment of image classifications (Step 3, under section “Classification of GE Images”).

2.3. Image classification

Step 1: Georeferencing and definition of lake boundaries and buffer zones

The downloaded images were georeferenced using the Georeferencer tool in Quantum Geographic Information System (QGIS) 3.30.1 whereby at least four clearly defined control points were selected such as road intersections, corners of a major building, or sharp edge(s) of the lakes. We used the same control points to georeference all images of the same lake to ensure that all images of a lake placed at the same location in the geographical coordinate system. Boundaries of the lake were manually drawn by using the “Add polygon” feature of GE 7.1 on the oldest image as a baseline boundary of the lake. Afterwards, the digitized lake boundary was exported as a kml file and converted into a shapefile in QGIS 3.30.1. Buffer zones (multi-ring donuts’ structure) of 300 m were defined for field sampling based on the shapefile of the lake boundary.

Step 2: Definition of classes

The internal area of each lake was assigned to four classes: algae, macrophytes, surface water, and dried land. The latter represented the bare soil areas inside the lake boundary that resulted from lake dry-ups, lake banks, or were island areas (Bareuther et al., 2020). Buffer zones were assigned to the two binary categories “built-up” and “non built-up” (Chan et al., 2008).

Step 3: Classification of GE images

A minimum of seven training polygon inputs were generated in each class with the Semi-Automatic Classification Plugin (SCP) of QGIS. Region of Interest (ROI) polygons and spectral signatures were stored for further classification of GE images. The training inputs of the built-up class were re-used from earlier images if there were no spectral differences between them. In total, approximately 6000 training polygons were created for supervised classification with the Maximum Likelihood algorithm in QGIS following the method applied by Bareuther et al. (2020). Training inputs were evaluated by Jeffries-Matusita distance and the training set was re-created if the values were < 1.8 as recommended by Richards & Jia (2006). The number of polygons in a training set was increased if the Jeffries-Matusita distance value was < 1.8. In-field cluster-wise GTPs were also collected in June 2021 in which similar spectral reflectances between algae and young macrophytes in GE images were deciphered.

Step 4: Post-classification

Post-classification was used to calculate the area of each class by masking it with respective lake boundaries and buffer boundary shapefiles. The masked raster images were then converted into shape files and the area of each class was determined using a geometry calculator rather than post-classification in QGIS.

Step 5: Accuracy assessment

To calculate the accuracy of each image classification an accuracy assessment process using the post-processing feature of the SCP plugin

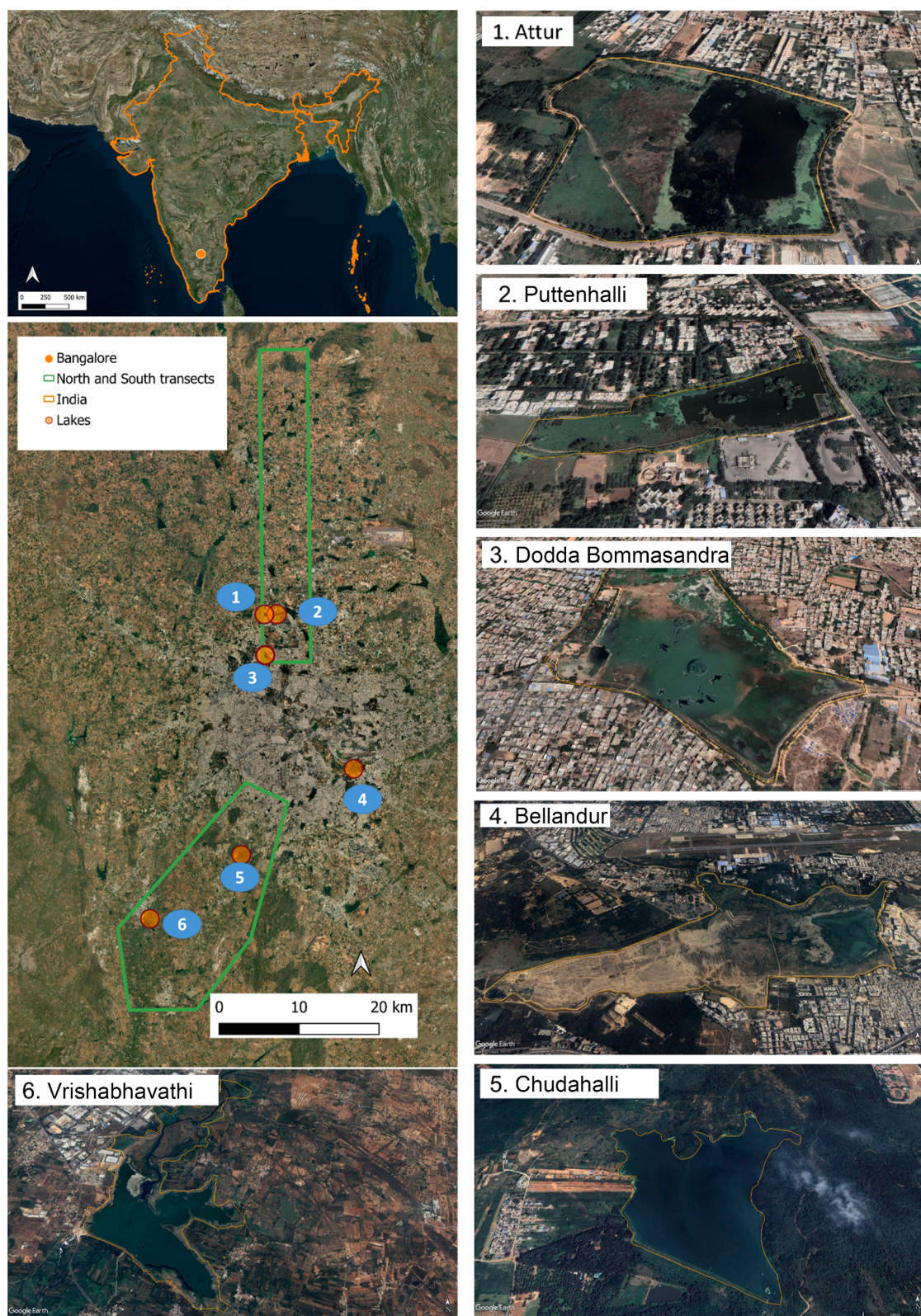


Fig. 1. Study locations in the Bengaluru area of South India 2022/2023 satellite images (Sources: Google Earth Pro 7.1 and base map in QGIS, retrieved on 23.02.2023).

was performed by selecting a raster file of the classified image and a vector file of validation inputs. The objective of accuracy assessment is to quantitatively evaluate the effectiveness of pixel sampling in correctly representing the various land cover classes. In total, approximately 4000

polygons were used. Through this process, the overall accuracy, the user's and producer's accuracies, and the Kappa statistics from the error matrices were determined to evaluate the accuracy of the maps produced. Whenever overall accuracy was $< 60\%$, the number of polygons

Table 1

List of satellite images collected from Google Earth Pro 7.1 in Bengaluru, South India.

Name of lakes	Strata (1 rural, 2 peri-urban and 3 urban)	Number of images	Period
Attur	2	28	2004–2021
Bellandur	3	36	2002–2022
Chudahalli	1	26	2004–2022
Dodda Bommasandra	3	27	2002–2021
Puttenahalli	2	31	2004–2020
Vrishabhavathi	1	14	2004–2019
Total of images		162	

of the validation inputs was increased to improve overall accuracy. The mean accuracy evaluation within the lakes indicated a median of 97 %, displaying a strong correlation (0.97 Spearman rank correlation) with the Kappa coefficient (0.95 median) obtained during the classification of land classes within those lakes. Likewise, the median accuracy assessment within the buffer zones surrounding all the lakes stood at 97.15 %, also exhibited a significant correlation (0.92 Spearman rank correlation) with the Kappa coefficient (0.89 median) calculated for the buffer area classification (refer to Appendix T2 and Appendix T3).

2.4. Data analysis

The data was analyzed using R (4.1.0; R Core Team, 2022). For each lake, analyses were conducted separately to account for lake characteristics. Classified lake maps were used to calculate the area of built-up, non-built-up, water, macrophytes, algae, and dried land in square meters (m²) using QGIS (Step 4). The proportion of built-up area relative to the total buffer zone was calculated to visualize trends and proportions of each lake. Using proportions instead of total areas allow to accommodate different lake sizes, making comparisons between lakes more meaningful at the same scale. The sum of the built-up and non built-up area was the same (<0.001 %) across all photos per lake.

To understand the vegetation dynamics of individual lakes, the percentages of algae, macrophytes, water, and dried land were calculated whereby the sum of these values was similar for each lake (<0.005 %). As before, percentages instead of total areas were used to accommodate for varying lake sizes associated with year and month, accounting for the time differences between different images and different lake size. To investigate effects of urbanization-related encroachment on lakes, the variable "wet surface area" was defined. This comprises water, macrophytes, and algae, as they are interconnected whereby water areas might be hidden by macrophytes. The correlations between built-up, non-built-up, dried surface area, and wet surface area were calculated for each lake to explore their relationships.

Correlations between daily rainfall and minimum/maximum air temperature and wet surface area of the studied lakes were determined to assess the impact of climate on ecosystem dynamics. These climate data were obtained from an automatic weather station set up inside the GKVK campus of the University of Agricultural Sciences, Bengaluru. Correlations were calculated by taking the average minimum and maximum temperatures for the month corresponding to each photo. Subsequently, correlations were computed between the monthly average temperatures and the month of the photo. For correlations with rainfall, total rainfall during the wet season (June to September inclusive) was aggregated and associated with the following dry season. For example, images from March 2008 were linked to rainfall data from June to September 2007.

3. Results and discussion

3.1. Seasonal and temporal dynamics of vegetation

At lake classification, there was a distinction between macrophytes and algae (or protists) as non-vegetative categories comprised dried land and water. Some similarities between the lakes were observed: within a dry season, the vegetation was highly dynamic over relatively short periods confirming results of Bareuther et al. (2020). Within a month, the coverage of macrophytes and algae may significantly increase due to the fast growth rate of macrophytes (Fig. 2). However, it can also be reduced due to frequent fodder harvests by farmers and dredging by the lake governing authority. Harvesting and dredging may explain the limited correlation between macrophyte growth and climate at the smaller scale. Here the quick growth spurt may be substantially offset by a swift harvesting of vegetation as animal fodder (Alam et al., 2023) or dredging before satellite imaging.

3.1.1. Urban lakes - Dodda Bommasandra and Bellandur

Both urban lakes experienced an increase in water levels over the two studied decades, accompanied by a decrease in algae and an increase in macrophytes (Fig. 3). In Dodda Bommasandra, the increase in macrophytes was likely due to the rise in runoff flow in recent years, resulting in higher water and nutrient contents. The increased macrophyte growth, along with the rise in water runoff, has likely resulted in a decrease in dried-up land inside the lake. On the other hand, in Bellandur, the increase in macrophytes can be attributed to changes in the lake's immediate surrounding. The western lake side has become partly silted over time, creating a more favorable environment for perennial grasses to thrive (Ramachandra et al., 2017). However, the area covered by algae has significantly decreased despite the expansion of the water area. The reason for this decline might be that the water only remains in the heavily silted lake for a short period after which it overflows to nearby areas, preventing algae from thriving. Unlike in Dodda Bommasandra, Bellandur Lake has experienced an increase in dried land over the last two decades. This reflects the rapid urbanization surrounding this lake. After the year 2000, large-scale conversion of Bellandur's watershed area into residential and commercial layouts occurred, likely altering the hydrological regime and increasing silt movement into the catchment area inside the lake or low-lying areas. Furthermore, ongoing unplanned construction activities throughout the year often resulted in debris being dumped in the easiest accessible lake area (Ramachandra et al., 2017).

3.1.2. Peri urban lakes - Attur and Puttenhalli

During the observation period, Attur Lake has been repeatedly drained or blocked making it difficult to discern trends within a season. Out of 29 data points, 17 observations show no water surface and thus no algae growth. Nevertheless, the macrophyte area increased and the dried land declined during the latter part of the study period. This likely reflected rejuvenation activities such as dredging allowing accumulation of water at the eastern lake side.

Puttenhalli Lake was declared a Bird Conservation Reserve on 5 June 2014. The treatment plant at its eastern corner was insufficient to treat the heavy inflow of sewage water resulting in an increase in the water surface area, a stable macrophyte level, a decrease in the algae area, and a slight increase in the dried land due to continuous siltation process near the run-off inlet at the western side. We detected an antagonistic relationship between macrophytes and algae similar to the vegetation dynamics of other lakes.

3.1.3. Rural lakes - Vrishabhavathi and Chudahalli

Both rural lakes displayed a strong negative correlation between water surface area and macrophytes (Appendix T1). This correlation may be due to the interconnectedness of these lakes along a stream. While Chudahalli is located in the center of the stream, Vrishabhavathi

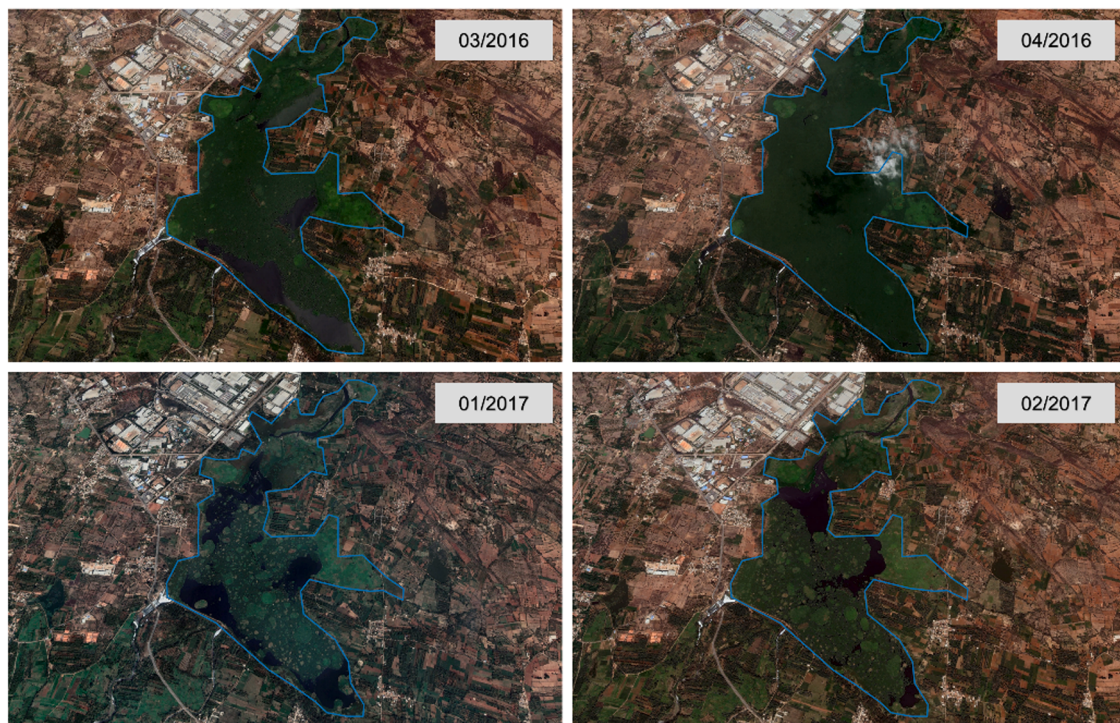


Fig. 2. Visualization of vegetation changes within a month for Vrishabhavathi Lake (Bengaluru) in 2016 and 2017 at the same scale (Sources: Google Earth Pro 7.1, retrieved on 20.01.2021).

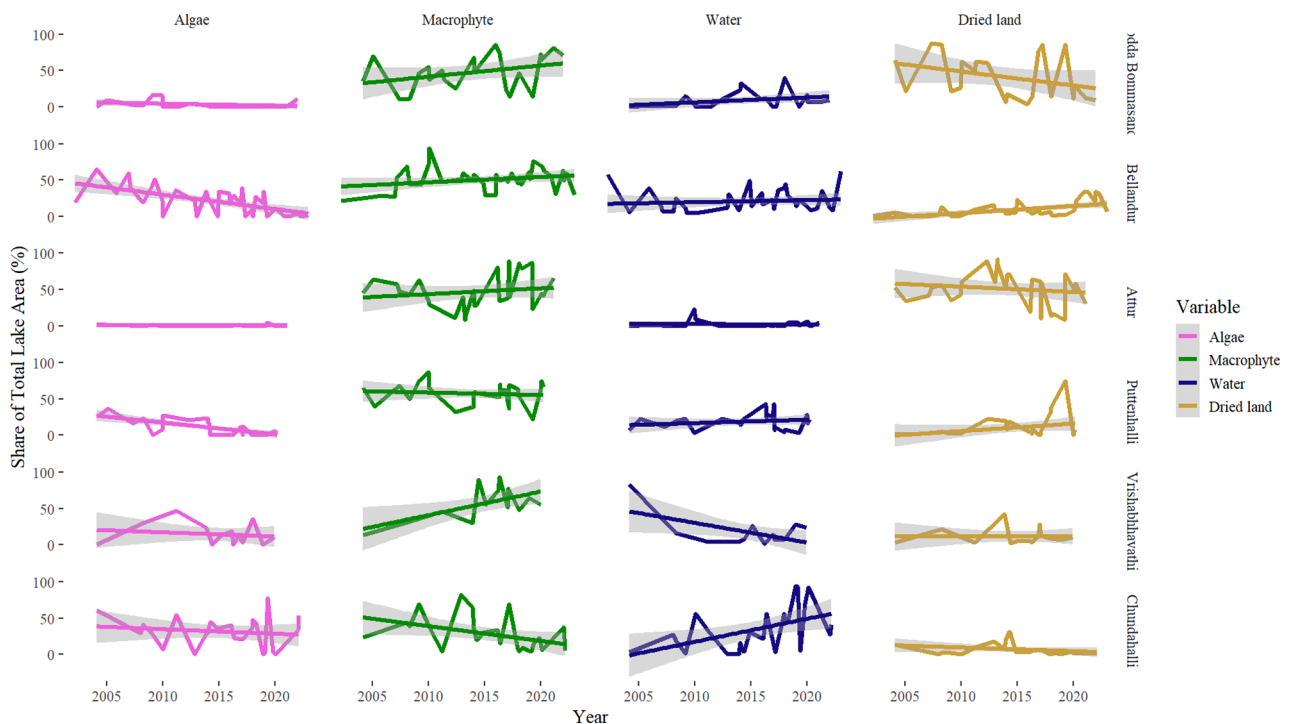


Fig. 3. Percentage changes in algae, macrophytes, water surface, and dried land along with variance in data over two decades for six lakes in Bengaluru, South India.

is situated at its base where the water flow has substantially slowed down (Fig. 1). However, despite both lakes being in rural areas, there are notable differences in the trends observed for Vrishabhavathi and Chudahalli. Chudahalli Lake lies downstream of the south-west watershed catchment area. Consequently, any surface sealing of the upstream area by buildings leads to increased runoff and silting downstream. As a result, downstream reservoirs such as Chudahalli Lake, experience

flooding. The increased flow of water in the mainstream area means that vegetation, including macrophytes, not remain in the water for extended periods. The increase in water surface area may thus be attributed to the large volume of water runoff and relatively lower cover by macrophytes and algae. As the water surface increases, the extent of dried land decreases (Fig. 3).

On the other hand, Vrishabhavathi Lake functions more as a water

reservoir than as a traditional lake. As such, it receives municipal and industrial wastes from Bengaluru, resulting in the reservoir carrying high loads of nutrients and contaminants. The surface water area is relatively stable even if the reservoir lacks tight bunds or walls on the eastern side, allowing water to flow freely in that direction. This reservoir contains perennial grasses and water hyacinths as part of the macrophyte class. Due to the inflow of additional nutrients, the macrophyte population has increased and covered most of the water surface. The presence of macrophytes likely suppressed to the growth of algae (Mohamed, 2017). Over the two decades, water surface and algae covered areas have decreased (Fig. 1). However, even taking into account the limited data points available before 2014, the water surface area and algae levels appear to be relatively stable and the fluctuation in water surface area may be due to the growth of macrophytes. The area of dried land seemed to remain stable in this reservoir because it receives municipal and industrial wastewater throughout the year.

3.2. Expansion of built-up areas surrounding the lakes

Urbanization around Bengaluru's lakes depends upon the intensity of the urban-rural transformation processes (Fig. 4). The expansion of the built-up areas around the lakes varies according to the location of the lakes. Urban lakes are obviously more exposed to the effects of growing built-up areas than peri-urban or rural ones (Fig. 5; Chakraborty, 2022). Each lake's surroundings have different trajectories of evolution

(Appendix F1).

3.2.1. Urban lakes - Dodda Bommasandra and Bellandur

Dodda Bommasandra has the highest share of built-up area within the buffer zone. In 2004, it occupied 47 % of the total buffer area, and exceeded 60 % in 2014 with little change until 2021 (Fig. 5). For Bellandur Lake, which historically was used for the cultivation of paddy rice (*Oryza sativa* L.) and vegetables as well as for fishing (D'Souza, 2007), the built-up area within the 300 m buffer zone has increased from 13 % in 2005 to 23 % in 2013, before decreasing to 15 % in 2020. This trend may be caused by misclassification of dumping areas around the lake as built-up areas. This is indicated by two big spots classified as built-up areas in 2013 on the eastern side and the south-western side in 2020 which have turned into green areas by 2020 (Fig. 6).

3.2.2. Peri-urban lakes - Attur and Puttenhalli

The 300 m buffer around Attur has experienced a steep rise (2 % to 33 %) in the built-up area from 2004 to 2014, and a further increase to 38 % from 2014 to 2021. This location is well-connected with easily accessible rail and metro lines and nearby (within 5 km) the major road network of Doddaballapur and Bellary road (NH-44) that connects to the Kempegowda International Airport of Bengaluru. This confirms earlier reports that Bengaluru's growth pattern is polycentric in nature and growth in peripheral areas (Nagendra et al., 2013; Taubenböck et al., 2009).

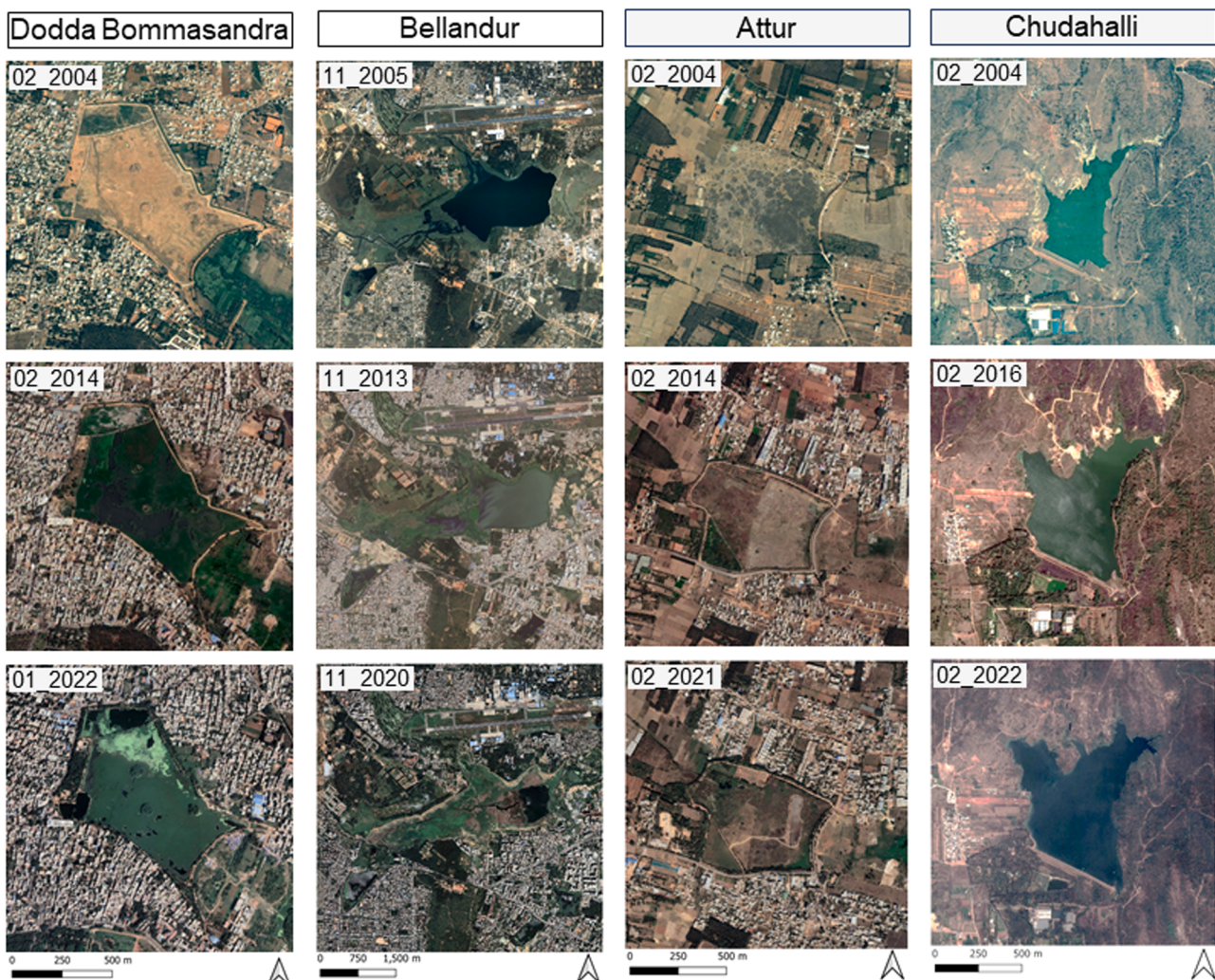


Fig. 4. Increase in built-up areas in the four lakes in Bengaluru, South India, (Image source: Google Earth Pro 7.1, retrieved on 23.03.2023).

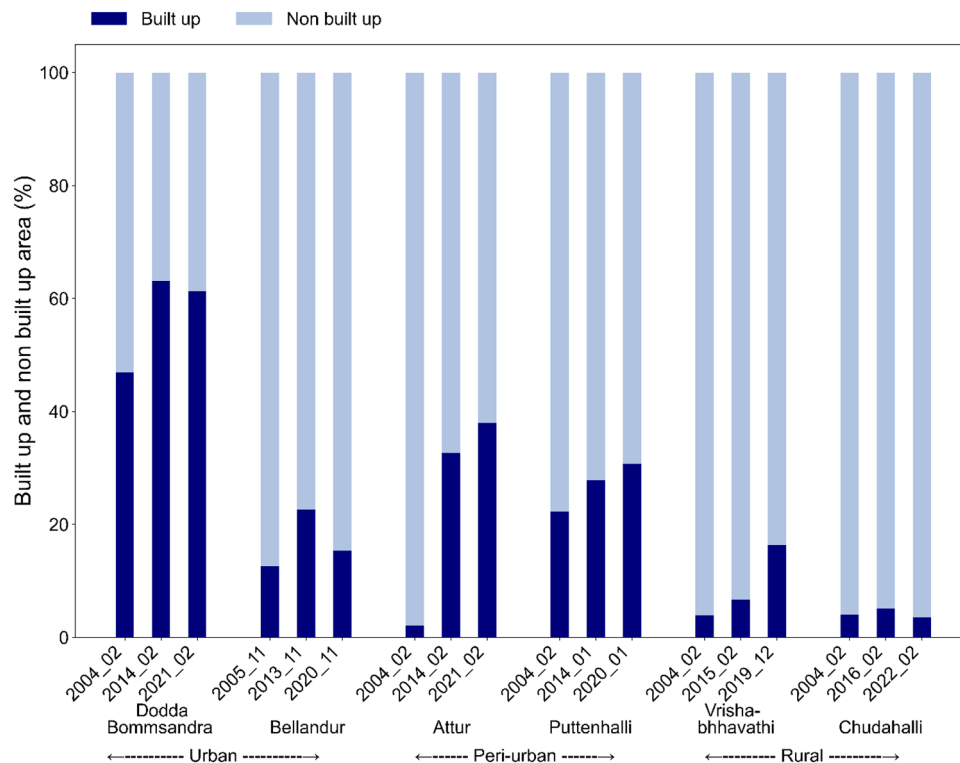


Fig. 5. Trend of built-up areas along the urban-rural gradient in Bengaluru, South India.

In 2004, Puttenahalli Lake was primarily surrounded by some commercial buildings and residential layouts. In 2008, Bengaluru Metropolitan Transport Corporation (BMTC) started building a bus depot in the south-eastern part of the buffer zone and after three years, Karnataka Power Transmission Corporation Limited (KPTCL) started establishing a power station in the north-eastern part of the buffer area. Therefore, the built-up area around this lake has experienced a consistent increase of about 5 % in each time interval (Fig. 5).

3.2.3. Rural lakes - Vrishabhavathi and Chudahalli

A rapid increase in built-up area from 6.5 % to 16.0 % from 2015 to 2019 was detected in Vrishabhavathi. Since 2007–08, Toyota and other steel and auto part companies have started establishing their plants along the western side of this reservoir. Consequently, engineering colleges and residences started developing around this area causing a high increase in built-up areas. In contrast, the built-up area around this lake remained constant throughout the study period in Chudahalli Lake which is known for its picnic spots in the countryside. Built-up area mainly consists of a resort and some mud roads along the lake buffer zone. Therefore, the slight deviation in the built-up area may reflect misclassification errors due to seasonal changes in vegetation.

3.3. Lake ecosystems along urban-rural gradient

The dried surface area in each lake which represents the loss of water surface exhibit varying correlations with the surrounding built-up (Table 2). These correlations can be attributed to the unique characteristics of each lake, such as embankments around the lakes, depth of the lakes, and connectivity with other bodies of water. These variations underscore the nuanced nature of lake ecosystems, where diverse factors play crucial roles in shaping the relationships between urbanization and the extent of dry lake surface. Interestingly, no clear pattern of the dry surface area within lakes emerged along the urban-rural gradient. This suggests that the effects of urbanization on lakes are not uniform but rather site-specific. Satellite image-based identification of lake areas

filled with silt was challenging, whereby in our case, only true color images were used to identify water and dried land without high additional spectral information. However, even with this limitation our approach yielded insights into the increasing dry surface area of urban lakes such as Bellandur, which is susceptible to disposal of sewage water and construction debris (Prasad, 2019; Bharath and Umesh, 2017). The depth of the lakes should also be regularly measured to assess the rate of siltation in each lake. Such monitoring will provide a better understanding of these ecosystems.

The wet surface area of urban and peri-urban lakes, increased with rainfall (Table 3). However, the correlation coefficient between rainfall and wet surface area varied across different lake types. For the smaller lakes, such as Attur and Dodda Bomsandra, we observed a stronger positive correlation while larger lakes like Puttenhalli and Bellandur exhibited only moderate positive correlation. The perennial lakes, Vrishabhavathi and Chudahalli, showed the lowest correlation. Correlation between temperature and wet surface area was negative in all lakes except Vrishabhavathi Lake. This exception may be attributable to its shallow depth and supply of water from distant sources, maintaining a year-round availability of water. Interestingly, rural lakes showed also a negative correlation with rainfall while urban and peri-urban lakes showed a positive correlation. We recommend further investigation on plant growth on lakes and correlation between lake size, depth with climate and vegetation of urban and rural lakes.

4. Conclusions

Our study shows that the density of built-up areas around lakes decreases along the urban-rural gradients. The increase of built-up areas in the buffer zone does not always positively correlate with the wet surface area of the lakes. This disparity may point to factors such as the inflow of sewage water from other areas, or blockage and siltation. Our analysis underlines the importance of understanding lake vegetation dynamics due to urbanization at periphery. The data show that each lake has its own distinct characteristics, whereby the quality and quantity of sewage

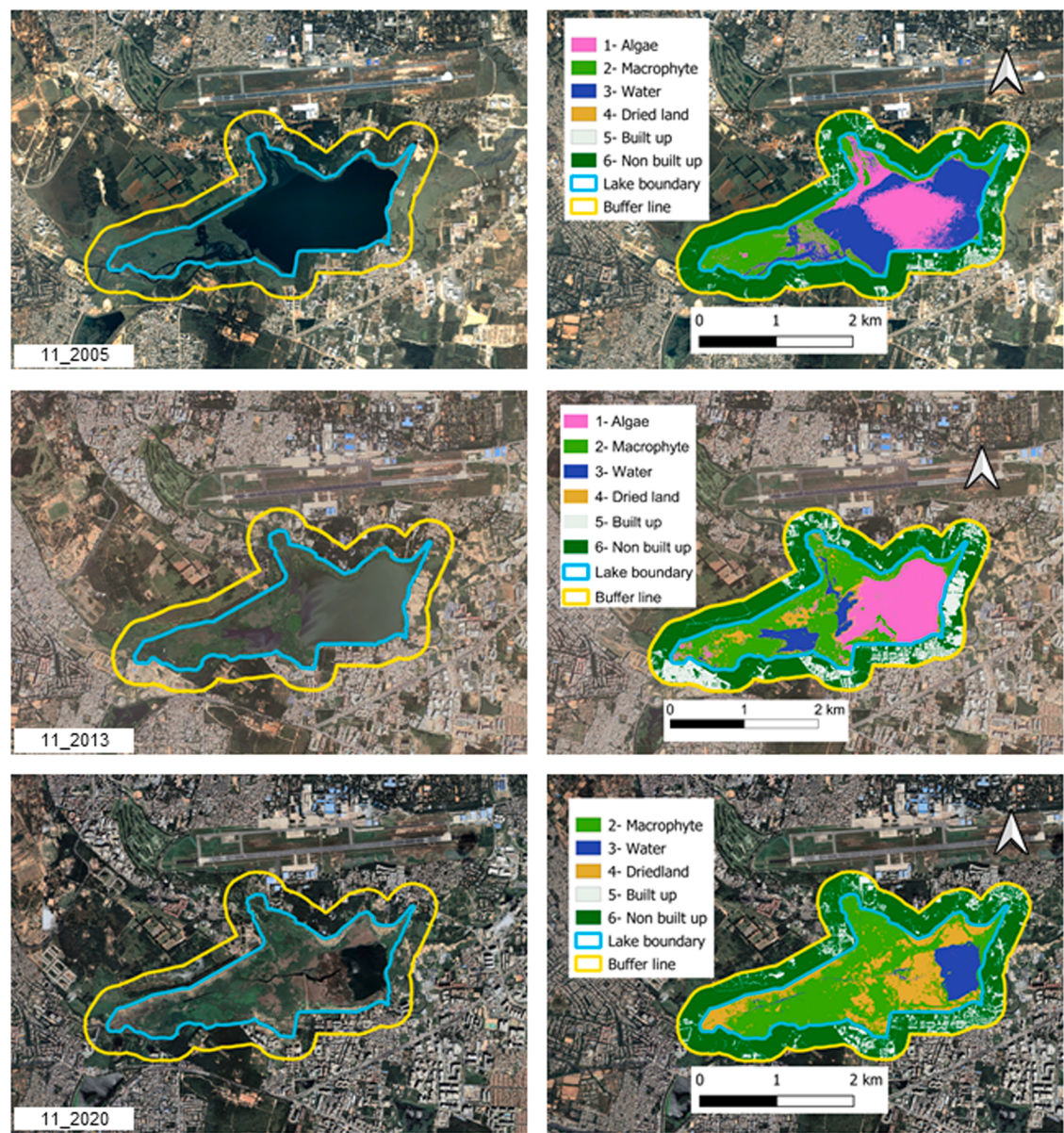


Fig. 6. Land use classification in Bellandur Lake, Bengaluru, South India using a supervised classification QGIS 3.22 (Image source: Google Earth Pro 7.1, retrieved on 23.03.2023).

Table 2
Correlations between built-up and dried surface for each lake along urban-rural gradient in Bangalore, South India.

	Urban		Peri-urban		Rural	
	Dodda Bomsandra	Bellandur	Attur	Puttenhalli	Chudahalli	Vrishabhavathi
Correlation with built-up areas	0.461	0.148	−0.076	0.362	0.438	−0.167

inflow interacts with the effects of peripheral built-up in the lake buffer zone and beyond. While our study contributes to a better understanding of the role of urbanization encroachment on lakes in Bengaluru, more profound analyses of its effects on ecosystem services would be interesting. This requires longer-term interdisciplinary studies with social-ecological surveys and field inventories.

CRediT authorship contribution statement

Suman Kumar Sourav: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal

analysis, Conceptualization. **Lily Clements:** Writing – review & editing, Validation, Methodology. **Thanh Thi Nguyen:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Data curation, Conceptualization. **Andreas Buerkert:** Visualization, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 3
Coefficient of the correlations between various climatic elements and wet surface area (water, macrophyte, and algae) in the six lakes in Bangaluru, India.

Gradient	Lake names	Minimum temperature	Maximum temperature	Rainfall in wet season
Urban	Bellandur	−0.192	−0.213	0.161
	Dodda	−0.414	−0.687	0.540
	Bommasandra			
Peri-urban	Attur	−0.306	−0.311	0.360
Rural	Puttenhalli	−0.253	−0.173	0.043
	Chudahalli	−0.424	−0.405	−0.029
	Vrishabhavathi	0.313	0.381	−0.384

Data availability

Data will be made available on request.

Acknowledgements

This work was conducted in the framework of the Indo-German Research Unit FOR2432 “Social–Ecological Systems in the Indian Rural–Urban Interface: Functions, Scales, and Dynamics of Transition” funded jointly by the Deutsche Forschungsgemeinschaft (DFG, Germany, Grant ID 279374797) and the Department of Biotechnology (DBT), Government of India.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.envc.2024.100944](https://doi.org/10.1016/j.envc.2024.100944).

References

Alam, M.S., Velayudhan, S.M., Dey, D.K., Adilieme, C., Malik, P.K., Bhatta, R., König, S., Schlecht, E., 2023. Urbanisation threats to dairy cattle health: insights from Greater Bengaluru. *India. Trop. Anim. Health Prod.* 55, 350. <https://doi.org/10.1007/s11250-023-03737-7>.

Bareuther, M., Klinge, M., Buerkert, A., 2020. Spatio-temporal dynamics of algae and macrophyte cover in urban lakes: a remote sensing analysis of Bellandur and Varthur wetlands in Bengaluru. *India. Remote Sens.* 12 (22), 3843. <https://doi.org/10.3390/rs12223843>.

Bharadwaj, V., Gupta, P.K., Siddiqui, A., 2022. Measuring and analyzing urban growth pattern using spatial metrics in Bengaluru. *India. Geocarto Int.* 37 (27), 15714–15735. <https://doi.org/10.1080/10106049.2022.2102222>.

Bharath, J., Umesh, Y., 2017. *Why Bellandur Lake Clean-Up Exercise Could Snap Many Human Linkages*. <https://economictimes.indiatimes.com/news/politics-and-nation/why-bellandur-lake-clean-up-exercise-could-snap-many-human-linkages/articleshow/58411010.cms>.

Bhat, S., Ramachandra, T.V., Mahesh, M., 2017. *Macrophytes of Bangalore Wetlands*. ENVIS Technical Report 126.

Brucet, S., Poikane, S., Birk, S., Lyche Solheim, A., 2013. Biological assessment of European lakes: ecological rationale and human impacts. *Freshw. Biol.* 58, 1106–1115. <https://doi.org/10.1111/fwb.12111>.

Carpenter, S.R., Lodge, D.M., 1986. Effects of submersed macrophytes on ecosystem processes. *Aquat. Bot.* 26, 341–370. [https://doi.org/10.1016/0304-3770\(86\)90031-8](https://doi.org/10.1016/0304-3770(86)90031-8).

Chakraborty, S., Maity, I., Dadashpoor, H., Novotný, J., Banerji, S., 2022. Building in or out? Examining urban expansion patterns and land use efficiency across the global sample of 466 cities with million inhabitants. *Habitat. Int.* 120, 102503 <https://doi.org/10.1016/j.habitatint.2021.102503>.

Chan, J.C.W., Demarchi, L., Van de Voorde, T., Canters, F., 2008. Binary classification strategies for mapping urban land cover with ensemble classifiers, IGARSS 2008 - 2008 IEEE International Geoscience and Remote Sensing Symposium, Boston, MA, USA, III - 1004-III -1007. <https://doi.org/10.1109/IGARSS.2008.4779522>.

D'Souza, R., 2007. *A Study On Bellandur tank and Changes Due to Urbanisation*. A CASUMM Publication, Bangalore, India.

Dittrich, C., 2007. *Bangalore: globalisation and fragmentation in India's hightech-capital*. *Asien* 103, 45–58.

Gautam, V.K., Gaurav, P.K., Murugan, P., Annadurai, M., 2015. Assessment of surface water dynamics in Bangalore using WRI, NDWI, MNDWI, supervised classification and KT transformation. *Aquat. Procedia* 4, 739–746. <https://doi.org/10.1016/j.aqpro.2015.02.095>.

Goldman, M., 2011. Speculating on the next world city. *Worlding Cities: Asian Experiments and the Art of being Global* 31, 229–258. <https://doi.org/10.1002/9781444346800.ch9>.

He, C., Tian, J., Shi, P., Hu, D., 2011. Simulation of the spatial stress due to urban expansion on the wetlands in Beijing, China using a GIS-based assessment model. *Landsc. Urban Plan.* 101 (3), 269–277. <https://doi.org/10.1016/j.landurbplan.2011.02.032>.

Hettiarachchi, M., Morrison, T.H., Wickramasinghe, D., Mapa, R., De Alwis, A., McAlpine, C.A., 2014. The eco-social transformation of urban wetlands: a case study of Colombo, Sri Lanka. *Landsc. Urban Plan.* 132, 55–68. <https://doi.org/10.1016/j.landurbplan.2014.08.006>.

Hoffmann, E., M., Jose, M., Nölke, N., Möckel, T., 2017. Construction and use of a simple index of urbanization in the rural–urban interface of Bangalore. *India. Sustainability* 9 (11), 2146. <https://doi.org/10.3390/su9112146>.

Mahapatra, D.M., Joshi, N., Ramachandra, T.V., 2018. Insights to bioprocess and treatment competence of urban wetlands. *J. Environ. Manage.* 206, 1179–1191. <https://doi.org/10.1016/j.jenvman.2017.10.054>.

Martínez-Arroyo, A., Jáuregui, E., 2000. On the environmental role of urban lakes in Mexico City. *Urban. Ecosyst.* 4, 145–166. <https://doi.org/10.1023/A:1011355110475>.

McDonald, R.I., Green, P., Balk, D., Fekete, B.M., Revenga, C., Todd, M., Montgomery, M., 2011. Urban growth, climate change, & freshwater availability. *PNAS USA* 108 (15), 6312–6317. <https://doi.org/10.1073/pnas.1011615108>.

Mohamed, Z.A., 2017. Macrophytes-cyanobacteria allelopathic interactions and their implications for water resources management—a review. *Limnol.* 63, 122–132. <https://doi.org/10.1016/j.limno.2017.02.006>.

Nagendra, H., Sudhira, H.S., Katti, M., Schewenius, M., et al., 2013. Sub-regional assessment of India: effects of urbanization on land use, biodiversity and ecosystem services. In: Elmqvist, T., et al. (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_6.

Naselli-Flores, L., 2008. *Urban Lakes: ecosystems at Risk, Worthy of the Best Care*. In: *Materials of the 12th World Lake Conference, 2007*. Taal, pp. 1333–1337.

Parikh, J., Sandal, G., Jindal, P., 2015. Climate resilient cities: vulnerability profiling of twenty Indian cities. *Dev. India* 351–365. https://doi.org/10.1007/978-81-322-2541-6_16.

Prasad, P., 2019. Slum sprawl, Debris Dumping On Rise Near Bellandur lake. *The New Indian Express*. Retrieved on September 21, 2023, from. <https://www.newindiaexpress.com/cities/bengaluru/2019/jul/30/slum-sprawl-debris-dumping-on-rise-near-bellandur-lake-2011362.html>.

R Core Team, 2022. *R: A language and Environment For Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>.

Ramachandra, T.V., Aithal, B.H., 2019. *The Wiley Blackwell Encyclopedia of Urban and Regional Studies*. Bangalore. John Wiley and Sons, Hoboken, NJ, USA, pp. 1–21.

Ramachandra, T.V., Aithal, B.H., 2016. Bengaluru's reality: towards unlivable status with unplanned urban trajectory. *Curr. Sci.* 110, 2207–2208.

Ramachandra, T.V., Kumar, U., 2008. Wetlands of greater Bangalore, India: automatic delineation through pattern classifiers. *Electron. Green J.* 26 (26) <https://doi.org/10.5070/G312610729>.

Ramachandra, T.V., Mahapatra, D.M., Vinay, S., Varghese, S., Asulabha, K., Bhat, S., Aithal, B.H., 2017. *Bellandur and Varthur Lakes Rejuvenation Blueprint*, ENVIS Technical Report 116. Environmental Information System, CES, Indian Institute of Science, Bangalore, India.

Ramachandra, T.V., Ahalya, N., Payne, M., 2003. Status of Varthur Lake: Opportunities for Restoration and Sustainable Management, Technical Report 102. Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.

Ramachandra, T.V., Asulabha, K., Sincy, V., Bhat, S., Aithal, B., 2016b. *Wetlands: Treasure of Bangalore*, ENVIS Technical Report 101. Energy and Wetlands Research Group, CES, Indian Institute of Science, Bangalore, India.

Ramachandra, T.V., Mahapatra, D.M., Bhat, S.P., Asulabha, K., Varghese, S., Aithal, B.H., 2014. *Integrated Wetlands Ecosystem: Sustainable Model to Mitigate Water Crisis in Bangalore*; ENVIS Technical Report 76. Environmental Information SystemCES, Indian Institute of Science, Bangalore, India.

Ramachandra, T.V., Sincy, V., Asulabha, K., Mahapatra, D.M., Bhat, S.P., Aithal, B.H., 2018. Optimal treatment of domestic wastewater through constructed wetlands. *J. Biodiversity* 9, 81–102.

Ramachandra, T.V., Vinay, S., Mahapatra, D., Varghese, S., Aithal, B.H., 2016a. *Water Situation in Bengaluru*. ENVIS Technical Report 114. Environmental Information System, CES, Indian Institute of Science, Bangalore, India.

Ravindrababu, B., Rajegowda, M., Janardhanagowda, N., Girish, J., 2010. Weekly, monthly and seasonal rainfall at Bengaluru in Karnataka. *J. Agric. Meteorol.* 12, 263–265. <https://doi.org/10.54386/jam.v12i2.1322>.

Richards, J.A., Jia, X., 2006. *Remote Sensing Digital Image Analysis: An Introduction*, 4th edition. Springer.

Sen, A., Nagendra, H., 2021. The differentiated impacts of urbanization on lake communities in Bengaluru. *India. Int. J. Urban Sustain. Dev.* 13 (1), 17–31. <https://doi.org/10.1080/19463138.2020.1770260>.

Søndergaard, M., Johansson, L.S., Lauridsen, T.L., Jørgensen, T.B., Liboriussen, L., Jeppesen, E., 2010. Submerged macrophytes as indicators of the ecological quality of lakes. *Freshw. Biol.* 55, 893–908. <https://doi.org/10.1111/j.1365-2427.2009.02331.x>.

Sudhira, H.S., Nagendra, H., et al., 2013. Local assessment of Bangalore: graying and greening in Bangalore – impacts of urbanization on ecosystems, ecosystem services and biodiversity. In: Elmqvist, T., et al. (Eds.), *Urbanization, Biodiversity and*

- Ecosystem Services: Challenges and Opportunities. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_7.
- Sudhira, H.S., Ramachandra, T.V., Raj, K.S., Jagadish, K.S., 2003. Urban growth analysis using spatial and temporal data. *J. Indian Soc. Remote Sens.* 31, 299–311. <https://doi.org/10.1007/BF03007350>.
- Taubenböck, H., Wegmann, M., Roth, A., Mehl, H., Dech, S., 2009. Urbanization in India—spatiotemporal analysis using remote sensing data. *Comput. Environ. Urban Syst.* 33, 179–188. <https://doi.org/10.1016/j.compenvurbsys.2008.09.003>.
- UN, 2019. *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. United Nations, Department of Economic and Social Affairs, Population Division, New York: United Nations.
- UN, Department of Economic and Social Affairs, Population Division, 2022. *World Population Prospects 2022: Data Sources*. (UN DESA/POP/2022/DC/NO. 9).
- Unnikrishnan, H., Mundoli, S., Nagendra, H., 2017. Making water flow in Bengaluru: planning for the resilience of water supply in a semi-arid city. *JSUPP* 2 (1), 63–72. <https://doi.org/10.18063/JSU2017.01.002>.
- Varalakshmi, L.R., Ganeshamurthy, A.N., 2012. Heavy metal contamination of water bodies, soils and vegetables in peri-urban areas: a case study in Bangalore. *J. Horticult. Sci.* 7 (1), 62–67. <https://doi.org/10.24154/jhs.v7i1.392>.
- Verma, R., Singh, S.P., Raj, K.G., 2003. Assessment of changes in water-hyacinth coverage of water bodies in the northern part of Bangalore city using temporal remote sensing data. *Curr. Sci.* 84, 795–804. <http://www.jstor.org/stable/24107584>.